Development of an Online Roadway Geometry Design Software for Transportation Education and Training

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ABSTRACT
Traditionally, students use pencil and ruler to lay out lines and curves over contour maps for roadway geometry design. Numerous calculations of stopping sight distance, minimum turning radius, and curve alignments are required during the roadway design process in order to ensure safety, to minimize economic and environmental impacts, as well as to reduce construction costs. Students usually perform iterative computations manually during the design process in order to meet any given design criteria and environmental constraints. The traditional process of roadway geometry design is often cumbersome and time consuming. The traditional approach limits students from taking a broader perspective of the overall roadway geometry design process. An Internet-based roadway design tool (ROAD: Roadway Online Application for Design) was developed to enhance the learning experience for transportation engineering students. This tool allows students to efficiently design and to easily modify the roadway design with given economic and environmental parameters. A 3D roadway geometry model can be generated by the software at final design to allow students immerse themselves in the driver's seat and drive through the designed roadway at maximum design speed. This roadway geometry design tool was deployed in a civil engineering undergraduate class in 2006 and 2007 at Department of Civil Engineering, University of Minnesota. Survey results from students indicated the ROAD software enhances their learning experiences in performing roadway geometry design.

KEYWORDS
Roadway Geometry Design, Distance Learning, Transportation Visualization

INTRODUCTION

The design of the modern roadway system is a sophisticated process that presents the transportation engineer with many challenges. A roadway designer often has to consider several design controls and criteria which go beyond the basic application of regulatory standards. Increasing traffic, cost of construction, the price of real estate, mix and sizes of vehicles, and environmental and ecological considerations are all part of the challenges that civil engineers face today. A properly designed roadway takes into consideration mobility and safety issues while addressing economic impacts and environmental constraints [1].

There are many geometric elements involved in roadway design, and the most important of which is alignment. Detailed guidelines of roadway geometry design are discussed in the "A Policy on Geometry Design of Highways and Streets 2004" [2] published by American Association of State Highway and Transportation Officials (AASHTO). Traditionally, students use pencil and ruler over contour maps to design roadway geometry. Substantial calculations of stopping sight distance, minimum turning radius, and curve alignments are conducted during the geometry design process in order to ensure safety, to minimize economic and environmental impacts, and to reduce construction costs. Students usually perform iterative calculations manually during the design process in order to meet certain design criteria and environmental constraints.

The traditional design process of roadway geometry design is often cumbersome and time consuming. It limits students from considering the overall roadway design process from a broader perspective. Many commercial software packages, used by practitioners and consultants, were developed by incorporating active digital maps, 3D design models and virtual reality walkthroughs to enhance the intelligence and connectivity for roadway design and planning process [3]. The commercial tools, designed for professionals, are usually complicated and expensive, and thus inappropriate for classroom use. Our development work does not intend to duplicate or even compete with the commercial packages. Our goal is to provide a simple web-based tool with necessary features that will allow students to better understand the process of roadway geometry design.

Internet-based roadway geometry design software (ROAD: Roadway Online Application for Design) was developed using the Java [12] programming language to simplify the road planning and design process. Our objective is to assist students conducting the roadway geometry design on a computer screen with an imported digital contour map as background for graphical design reference. Students will be able to design the geometry of a roadway more efficiently and effectively and thereafter spend more effort focus on strategic decisions, transportation planning, and potential environmental and economic impacts. Furthermore, the final roadway geometry design can be visualized in a 3D virtual reality environment using Virtual Reality Model Language (VRML) [4] from a web browser to examine the final roadway design in different perspective.

WEB-BASED ROADWAY GEOMETRY DESIGN

There are several commercially available software packages that offer flexible design of roadway geometry [5] and evaluate the impact of potential roadway design. However, these tools are generally complicated, expensive, and have a relatively steep learning curve. The intention of our development is not to re-invent the wheel but to provide a simpler tool with easy access for undergraduate students to better understand the design of roadway geometry. Web-based education has become a popular way of complementing classroom instruction recently. Online learning tools bring the classroom laboratory right in front of a student's computer. Web-based learning tool offer the benefit of platform independence and location independence. Users can access the learning tool virtually anytime and anywhere around the world using computers with Internet access.

Clearly, this approach can be integrated with other distance learning approaches already in place for teaching transportation technologies. For example, several web research modules were developed by ITS institute at University of Minnesota for high school students [13]. Liao et al. [6] developed a web-based traffic simulation framework for transportation training and education. Chen and Levinson [7] investigated the efficacy of using online simulation tool in teaching the topic of transportation network growth, conducted in a senior/graduate class in transportation system analysis, showing that the use of online simulation tool enhanced students' learning effectively. Helbing et al. [8] developed multilane freeway traffic models to help people better understand on-ramp vehicle merging, lane-changing, car following, lane-closing, and signal control through online traffic simulation and visualization [14].

Our Approach

The initial development of ROAD software focuses on the geometry design components and criteria. A digital contour map is used as background image for users to lay out their roadway designs. The web-based tool provides ease of design and modification of construction lines and horizontal and vertical curves. It also allows students to place the roadway construction line/curve on appropriate location with respect to the contour map and other environmental constraints. Vertical design includes the additional capability of adjusting vertical curve intersect point (PVI) in order to minimize earthwork (accumulation of cut and fill). The roadway design software tool can automatically generate design reports and mass diagrams for earthwork estimation. The ROAD software also includes features to allow users to save or load horizontal or vertical design separately. More detail instruction on using the ROAD software is included in the online user's manual [9].

Horizontal Geometry Design

A digital contour image file is imported to ROAD software as background. Necessary information on image resolution and contour map scale can be entered by users in the design settings screen as shown in Figure 1a. Other design criteria such as speed limit, maximum cut and fill, maximum grade, driver reaction time, minimum vertical curve length, minimum horizontal curve radius, maximum super elevation, road width, and lane width (as displayed in Figure 1b), need to be specified at the beginning of the roadway geometry design. After identifying the start and end location of desired roadway construction, students can initially use the line construction tool from the toolbar to lay out the draft roadway design by following the direction tangent to contour curves. For example, we would like to design a two-lane roadway from point C to D as shown in Figure 2. Horizontal construction line segments is generated by clicking on a desired starting location over the contour map then drag the mouse to a desired ending location. End points of linear segments can later be modified using the editing tool for further adjustment. A curve segment can be generated by using the curve construction tool with desired curve radius. Users can check the minimum curve radius requirement based on the design speed and maximum grade of the roadway. The newly created curve segment can thereafter be placed inside two crossover lines (as illustrated in Figure 2) as curve transition between two linear segments. The curve segment doesn't need to be placed exactly tangent to both lines initially. By selecting two crossover linear segments and a nearby curve, users can use the alignment tool under option menu to automatically calculate the tangent points and adjust the curve segment tangent to both adjacent line segments.

In general, the major considerations in horizontal alignment design include safety, grade, type of facility, design speed, topography and construction cost. In roadway geometry design, safety is always considered, either directly or indirectly. Topography controls both curve radius and design speed to a large extent. The design speed, in turn, controls sight distance, but sight distance must be considered concurrently with topography because it often demands a larger radius than the design speed. All these factors must be balanced to produce an alignment that is safe, economical, in harmony with the natural contour of the land and, at the same time, adequate for the design classification of the roadway or highway [2]. The iterative designing process becomes tedious and cumbersome when using the traditional ruler and pencil method.

The elevation information is labeled on the 2D contour map but not included in the image data file. Students will have to sequentially create landmark stations at every location where the contour curve intersects with the proposed roadway by using the station/landmark tool. Each tangent point should also be included as transition landmark between line and curve segment. Elevation information at each station has to be entered by users according to the nearby contour lines elevation data. List of stations can be displayed by clicking on the view/station landmarks tool as shown in Figure 3. The elevation of each station in horizontal design needs to be specified by users in order to prepare for the vertical curve design.

Vertical Curve Design

After completing the horizontal geometry design, vertical curve design is also required to ensure continuous grade variation for safety and driving comfort. Elevation information of each station is plotted versus the calculated horizontal road distance from the starting to the end station according to the trajectory in horizontal design. An elevation profile for vertical design is shown in Figure 4 as an example. Users can use the vertical curve construction tool to lay out the construction lines for vertical curve design. Preliminary construction lines begin at the starting station by clicking on the first landmark on the graph (Figure 4). Users then sequentially click on desired vertical point of intersect (PVI) over the elevation profile until reaching the ending station by double-clicking the last landmark (or using the end icon from the toolbar). After completing the preliminary vertical construction lines, students can drag the PVI point to adjust the lines with minimum cut and fill. Students can then use the vertical curve calculation tool to compute the vertical point of curvature (PVC) and the vertical point of tangency (PVT) of each vertical curve. The PVC, PVT, and PVI points are automatically calculated and identified as shown in Figure 4 with different markers. Stopping sight distance and curve length are calculated using the formulas suggested in the AASHTO design manual [2].

The cut and fill profile based on the designed vertical curve can also be displayed by clicking on the fill/cut icon from the toolbar as shown in Figure 5. The zero horizontal line in the cut and fill profile, as shown in Figure 5, represents the elevation of proposed vertical curve. Lines above zero imply elevation is higher than designed vertical curve, requiring earth removal, while lines below zero require additional earth fill. Maximum cut and fill constraints specified in the design settings are also plotted for references. When maximum cut/fill constraints are not met, users can easily identify the location that exceeds cut/fill constraints from the cut and fill profile, clear the designed vertical curve using the clear curves tool under the edit menu, and then adjust vertical curve by modifying the end points of the vertical curve construction lines in the elevation profile. Users can also redesign a different vertical profile by using the clear design feature under the edit menu to remove both vertical curves and construction lines.

The mass diagram of the roadway design can also be plotted as shown in Figure 6 to estimate the amount of earth work required along the roadway design. The final design report, as shown in Figure 7, includes the station location and elevation information, grade, and amount of total earthwork, can also be created automatically by the software after the final geometry design.

3D Animation

The 3D roadway model was created based on the geometric data from horizontal trajectory and the elevation data from vertical curve design using the Virtual Reality Modeling Language (VRML) [4]. A VRML client (plugin) is required (for example, Cortona VRML client is available for free download at Parallel Graphics [15]) to render the 3D animation. Other VRML clients are also available from the Web3D consortium [16].

Virtual reality models have been widely used for education (for example, virtual solar system; introductory astronomy at Indiana University [17]). Virtual reality offers many benefits such as allowing observation from a great distance, close-up examination, and providing students the opportunity for insights [10]. Traditionally, students validate their final roadway geometry design by verifying that all design criteria are met. They do not have the opportunity to visualize and examine the final roadway design. Generating a 3D roadway model in virtual reality environment allows students to examine and experience any potential sight distance issue which may not appear in separate calculation for horizontal and vertical design. In the 3D view, as shown in Figure 8, students can experience themselves in the driver's seat and drive through the designed roadway at maximum design speed. The 3D animation also provides the invaluable opportunity for students to evaluate potential safety and comfort concern at maximum design speed.

DEPLOYMENT

ROAD software [11] was deployed in a civil engineering undergraduate class, CE3201 – Introduction to Transportation Engineering, in 2006 and 2007 at University of Minnesota. A digital contour map as shown in Figure 10 was given to students to design a two-lane highway connecting a visitor center at location point 1 on the map. Two potential access points were proposed, point B and E on the map. Students were asked to design and recommend a route connecting visitor center to existing road network through point B or E. Alignment parameters and other design criteria as shown in Figure 1b were also provided to students for the design. Students were divided in groups for this roadway geometry design project. Each group consisted of two or three people. Each group was required to submit a short report (2-3 pages) describing their design including the horizontal & vertical alignments.

Evaluation and Results

At the beginning of project, a one-hour tutorial was given to students on how to use the ROAD software after the project description was handed out. Students have about 5 weeks to work on their design in Civil Engineering computer lab or from personal PC at home. In order to evaluate the effectiveness of the ROAD software, a survey was conducted in class after students turn in their project reports. A list of the survey questions is included in Figure 11. There were 60 students who returned the evaluation form in spring semester 2006. In fall semester 2006, we had 46 participants return the surveys. In both semesters, 80% of the undergraduate students were male and 20% were female. The results from both surveys, as displayed in Figure 11, indicated that students in fall semester gave higher score on average than those in spring semester. In both cases, students can work in groups of two or three people. In fall semester 2006, the ROAD software tool was introduced to students as an option, as compared to freehand method, for their roadway geometry design project. However, all students chose to use ROAD computer software for their final design.

Question #1: *Overall, the use of computer-aided tool makes me more enthusiastic about attending lab and/or working on project.* (0-9, 0 means strongly disagree, 9 means strongly agree).
The average score was 6.7 and 7.9 for spring and fall semester, respectively (Figure 11.a). Some students commented that using the computer aided tool for design will make the project easier. The tool allows them to gain real design experience and better understand road layout. The solutions of roadway geometry design project in the past were usually limited when using the traditional approach. Survey results indicated that the ROAD tool helps students to explore various designs within given constraints and finish project assignment in a timely manner.

Question #2: *Overall, this computer-aided design (CAD) approach enhances my learning.* (0-9, 0 means strongly disagree, 9 means strongly agree).
Generally speaking, most students agreed that the CAD approach enhanced their roadway geometry design experience. The average score was 6.9 and 7.5 for spring and fall semester, respectively (Figure 11.b). A few students thought they will use AutoCAD [18] for the roadway geometry design before the project assignment. ROAD helps students better understand the designing process and requirements of roadway geometry design in a broader perspective which includes the environment impact, roadway safety, project cost, and so on.

Question #3: *Overall reaction to the roadway geometry design software*. (0-9, 0 means frustrating, 9 means satisfying).
The average score of question #3 was 4.7 and 5.9 for spring and fall semester, respectively (Figure 11.c). There were questions and suggestions from students regarding saving the design file and deleting/editing horizontal landmark stations. Both recommendations were incorporated in the latest revision of the ROAD software. Further usability test of the Graphical User Interface (GUI) might be considered to make ROAD software more users friendly.

Question #4: *Construct roadway geometry on PC screen is straightforward.* (0-9, 0 means never, 9 means always).
As compared to traditional ruler and pencil approach, designing roadway geometry on computer screen is much simpler and easier to edit, according to a student's comment from the survey. The tutorial and demo session in class and recitation were helpful to get students started. Based on survey recommendations, additional features were added that allows user to specify and edit horizontal landmark station in no particular order. The average score was 5.7 and 6.4 for spring and fall semester, respectively (Figure 11.d).

Question #5: *Overall, the lab instruction helps me complete the lab assignment*. (0-9, 0 means strongly disagree, 9 means strongly agree).
The average score was 6.2 and 7.6 for spring and fall semester, respectively (Figure 11.e). We gave a one-hour lab instruction session to students at the beginning of the project assignment. According to the survey results, some students from spring semester would like to have more lab instruction (one more hour) to go through detail that will help them finish the project assignment more effectively.

Question #6: *User's manual or help document is confusing/clear*. (0-9, 0 means confusing, 9 means clear).
Online help document was embedded in the road software. A PDF version of user's manual was also available for download at the lab website. We provided a hardcopy of the user's manual to fall semester students. For spring semester, we only provide students the electronic copy of user's manual. The average score was 5.4 and 6.9 for spring and fall semester, respectively (Figure 11.f). According to student's recommendation, the online user's manual with index search for the ROAD software will be helpful. The online help document with index search was added in the latest development.

Question #7: *Overall, the information (from screen or manual) is effective in helping me complete the project*. (0-9, 0 means strongly disagree, 9 means strongly agree).
The average score was 5.6 and 7.2 for spring and fall semester, respectively (Figure 11.g). One comment from students noted that it would be helpful to explain the purposes of each tutorial step in the user manual. As

recommended by students, an additional feature was added to prompt for saving roadway geometry design before closing/exiting the program.

Question #8: *Additional information might be useful to help me learn.*
18 students in spring semester (10 in fall semester) responded that they would like to have more information. 23 students in spring semester (36 in fall semester) responded that existing information was sufficient. Some students wish to have additional tutorial session. Some students noted that they would need more guidance in the lab and more explanation on mass diagram and what station point to connect. These recommendations will be included the tutorial session in the future.

Question #9: *The 3D animation helps me visualize my horizontal and vertical curve design and stopping sight distance.* (0-9, 0 means strongly disagree, 9 means strongly agree).
The average score was 6.1 and 6.8 for spring and fall semester, respectively (Figure 11.h). Some students did not try the 3D animation due because (1) it is optional; (2) the VRML plug-in was either not installed or did not function properly on the lab computers. The 3D animation was offered to students to visualize their roadway design as an optional tool. It is not required to finish the project assignment.

Question #10: *Other comments regarding 3D visualization of roadway geometry design*:
Some comments from the survey including “I got to drive to visitor center”, “many views were nice”, and “oncoming traffic was insufficient to show potential problem area”.

Question #11a: *Time you spent to learn how to use the roadway design software*.
In spring semester, students on average reported spending 2.0 hours (standard deviation 1.4) to learn how to use the software. In fall semester, students spent 1.4 (standard deviation 1.0) hours on average to learn the software.

Question #11b: *After you know how to use the software, how long it took you to finish the lab assignment*.
After learning the software, students spent 2.8 hours (standard deviation 2.2) to finish the project. In fall semester, students spent 4.6 (standard deviation 3.2) hours to complete the project. (Note: In spring semester, students were required to design only one route from point B to visitor center, point 1 in Figure 10, as compared to 2 routes in fall semester.

Question #12: Overall, I am satisfied with the amount of time it took to complete the lab assignment. (0-9, 0 means strongly disagree, 9 means strongly agree).
The average score was 5.3 and 6.7 for spring and fall semester, respectively (Figure 11.i). Some comments from students are: “when all software was uploaded, it ran quickly and well”, “manual calculations are not necessary when computer design program is available”, “it was much faster than doing it by hand”, “it made the project a lot easier and allow us to try multiple designs much faster”, and “exceptional technical support”. According the survey results, students are generally satisfied with the amount of time spent on finishing their project.

CONCLUSIONS

This paper reports on the development of an online roadway geometry design tool to help students better understand the different aspects of roadway geometry design. Instead of using the traditional pencil and ruler approach, this computer aided tool allows students to effectively explore different geometry design within the specified constraint and evaluate the cost and benefit of their design. Overall, the survey result shows that the ROAD software helps students better understand the roadway design process and requirement. As indicated in question #2, ROAD enhances students learning experience in learning roadway geometry design. There are comments to allow more flexibility in editing horizontal design without increasing the complexity to use the software.

In fall semester 2006, a homework assignment was given to students to design single curve roadway geometry by hand prior to the lab project. The exercise helps prepare students to understand the design procedure and fundamental calculation of roadway geometry design. In order to provide students more time to familiarize themselves with the ROAD software, another exercise may be assigned to redo the single curve homework assignment using the ROAD software and compare the results from ROAD and previous manual design. One of the instructional challenges is the size (60~70 students each semester) of the CE3201 class, which is a required undergraduate engineering class. Students were divided in three recitation sessions for the roadway geometry design project in spring 2007. But more importantly the instructional challenges come from student's motivation of taking this mandatory class. We hope thought the assistance of ROAD software and in-class tutorials, students can better understand the procedures that transportation professionals take to solve the roadway geometry design problem. And through the use of ROAD software, students can explore different geometry designs that can fulfill given design constraints and requirements in real world applications.

FUTURE WORK

Currently we use the 2D contour image as background for the roadway geometry design. Elevation information at each station has to be entered sequentially and manually. In the future, we plan to develop an interface to import Digital Terrain Model (DTM) data. Elevation information can be extracted from the digital terrain model automatically. The digital terrain model can also be integrated in the 3D animation model to enhance the realism of the drive-through experience and identify potential safety concerns at the final roadway design. Visualize the final roadway design in 3D was optional in class project. However, it offers an important verification and validation tool in real world roadway design application by the professionals. We believe that by providing roadway geometry design which incorporates visualization tools available on the Internet along with the ability to investigate and analyze different cause and effect scenarios, students will better understand the potential impacts of their design.

The ROAD software will be available for coming introductory transportation engineering class. Further refinement and enhancement to the software will be made based on the feedback from students and instructors. We also would like to explore the opportunity of using the ROAD software for a senior/graduate level highway design class in the future.

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[17] Center for Research on Learning & Technology, Indiana University, http://vss.crlt.indiana.edu
[18] AutoCAD is a product of Autodesk Inc., http://www.autocad.com

LIST OF FIGURES

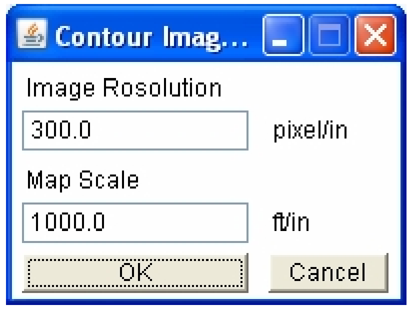


Figure 1a. Map and image settings

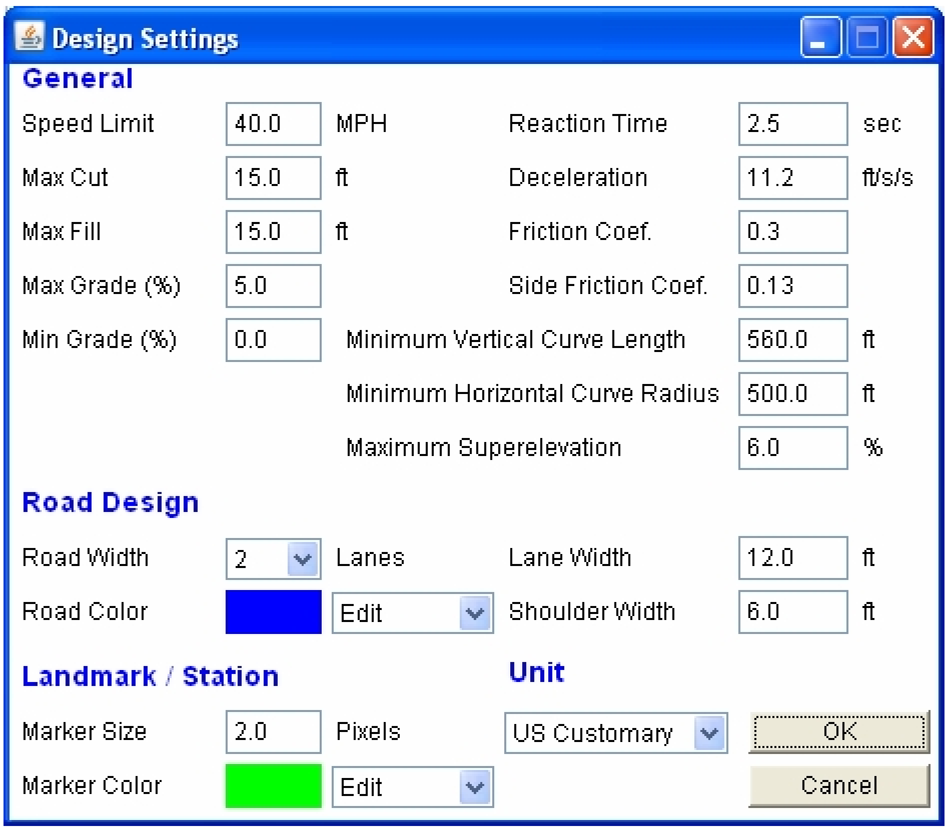


Figure 1b. Settings of roadway geometry design

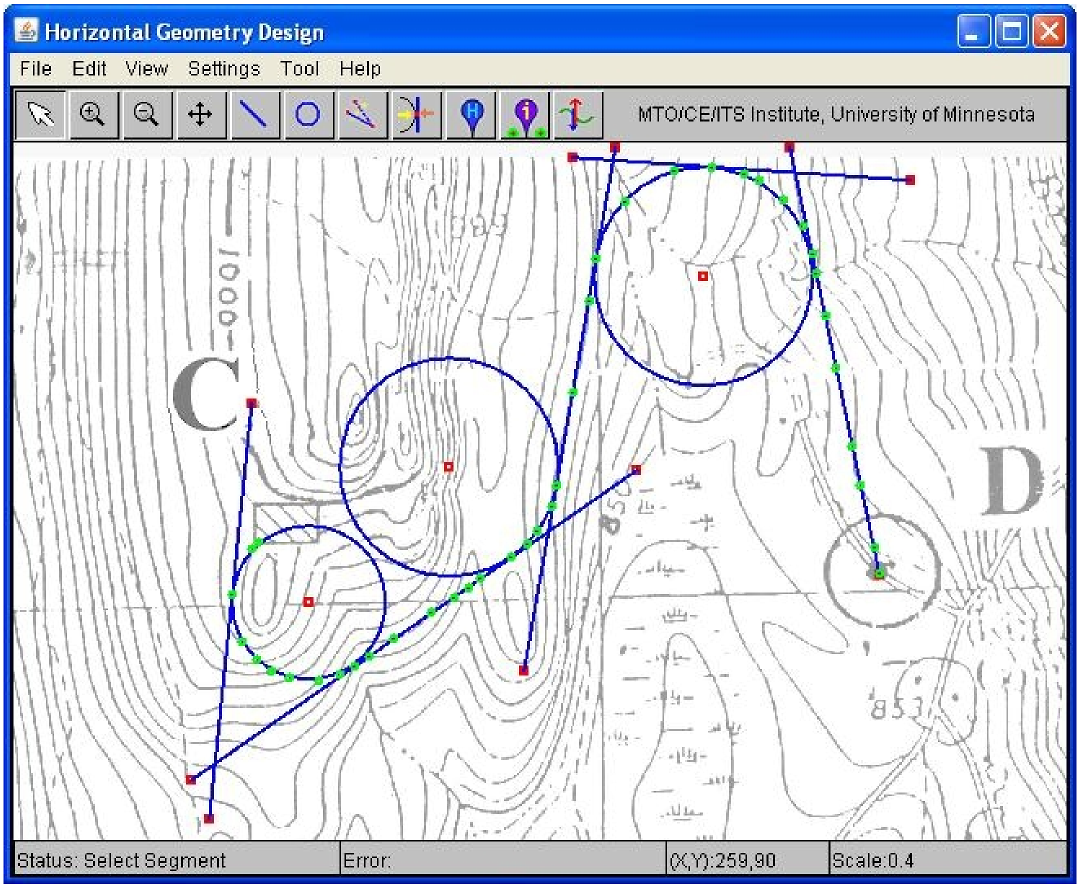


Figure 2. Horizontal geometry design

View Landmark Data

File Data

ID	POS X	POS Y	Elevation	Type
1	382.4	591.833	991.0	Curve
2	371.512	602.303	990.0	Curve
3	340.566	671.416	985.0	Tangent
4	356.731	744.567	980.0	Curve
5	378.519	771.52	970.0	Curve
6	401.803	788.355	960.0	Curve
7	428.665	799.239	950.0	Curve
8	473.296	802.651	940.0	Curve
9	506.046	794.194	930.0	Curve
10	528.453	781.932	920.0	Tangent
11	551.238	766.096	920.0	Line
12	589.399	739.573	930.0	Line
13	647.05	699.505	930.0	Line
14	680.081	676.548	920.0	Line
15	703.76	660.091	915.0	Line
16	721.991	647.42	920.0	Line
17	768.897	614.82	927.0	Tangent
18	793.275	594.202	920.0	Curve
19	809.555	574.84	920.0	Curve
20	830.333	536.27	910.0	Curve
21	838.97	504.7	908.0	Tangent
22	863.783	360.134	910.0	Line
23	887.674	220.944	910.0	Line

Figure 3. List of stations

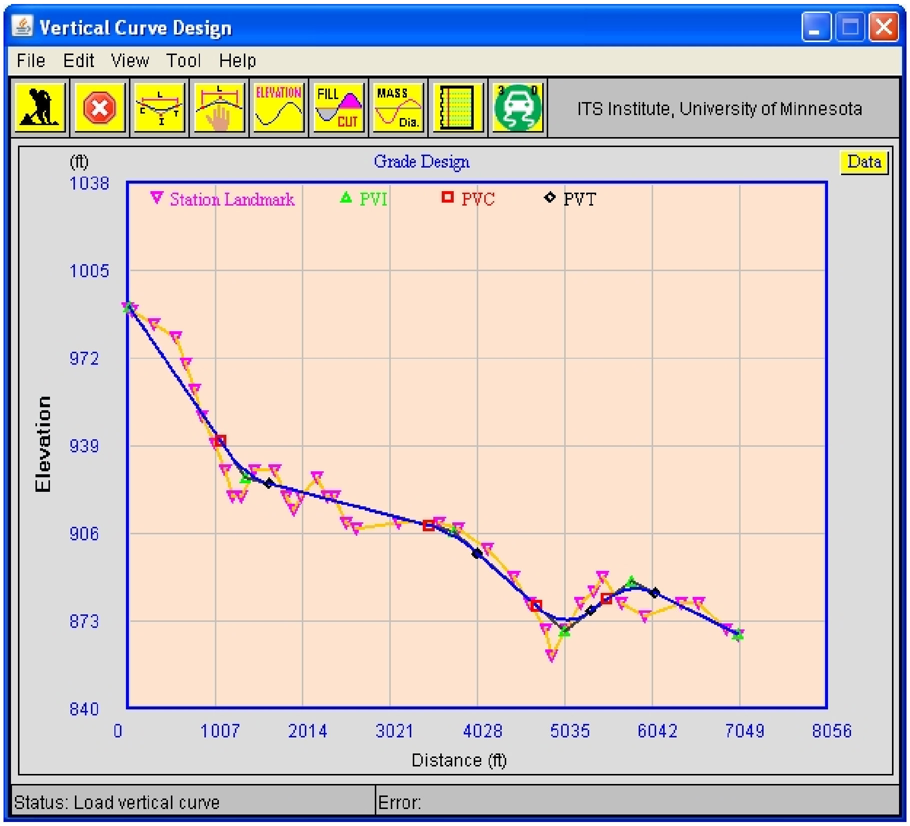


Figure 4. Vertical curve design – elevation profile

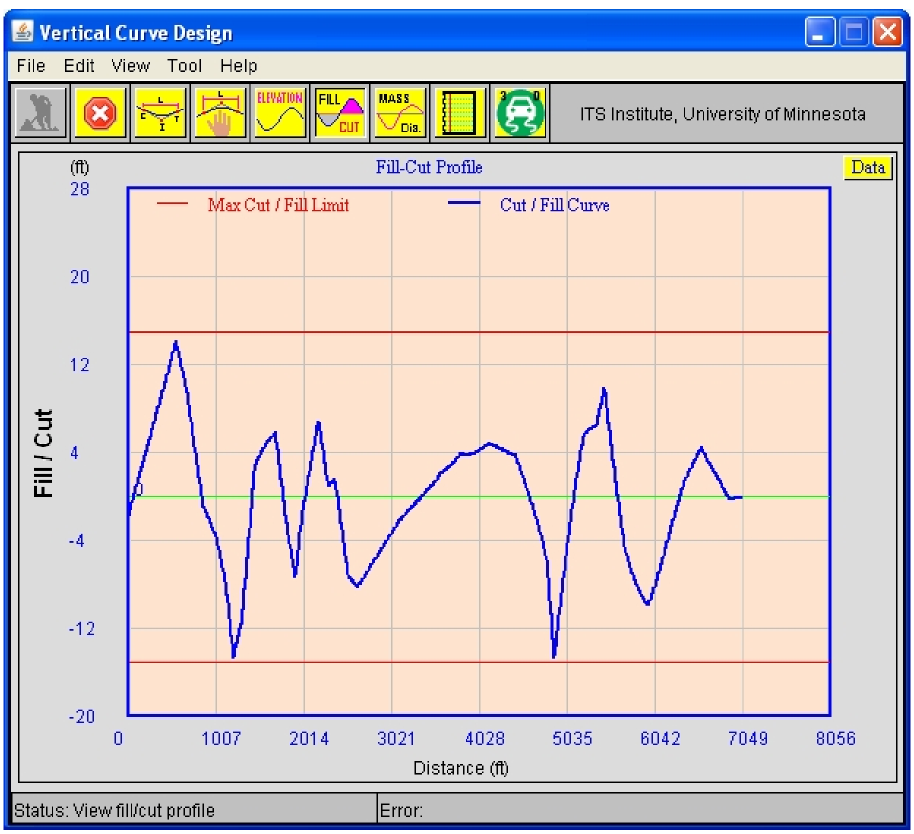


Figure 5. Vertical curve design – fill and cut profile

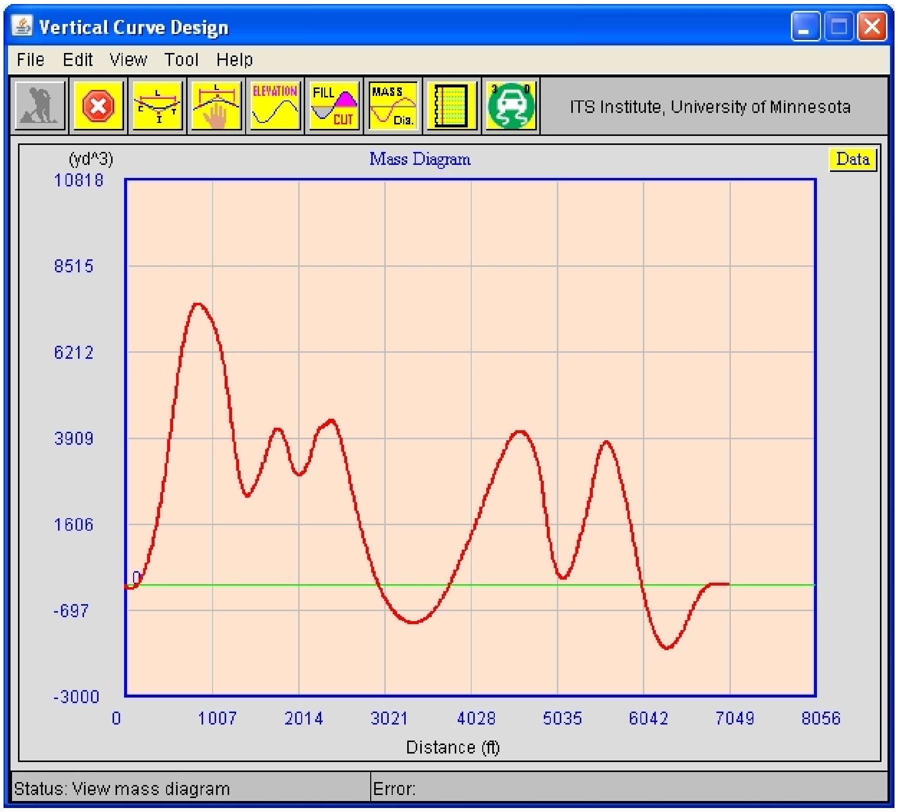
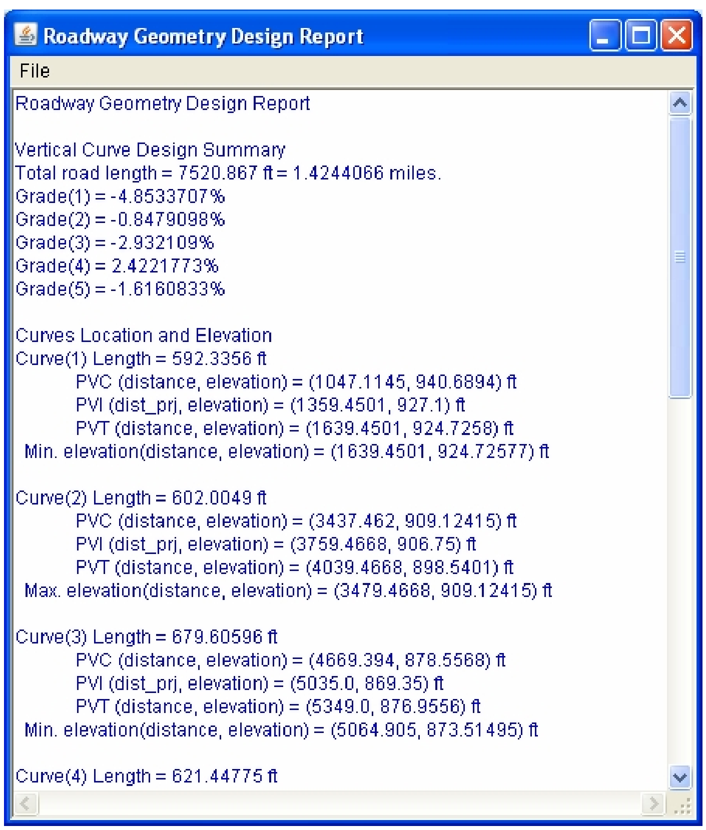


Figure 6. Vertical curve design – mass diagram


Roadway Geometry Design Report

File

Roadway Geometry Design Report

Vertical Curve Design Summary
Total road length = 7520.867 ft = 1.4244066 miles.
Grade(1) = -4.8533707%
Grade(2) = -0.8479098%
Grade(3) = -2.932109%
Grade(4) = 2.4221773%
Grade(5) = -1.6160833%

Curves Location and Elevation
Curve(1) Length = 592.3356 ft
PVC (distance, elevation) = (1047.1145, 940.6894) ft
PVI (dist_prj, elevation) = (1359.4501, 927.1) ft
PVT (distance, elevation) = (1639.4501, 924.7258) ft
Min. elevation(distance, elevation) = (1639.4501, 924.72577) ft

Curve(2) Length = 602.0049 ft
PVC (distance, elevation) = (3437.462, 909.12415) ft
PVI (dist_prj, elevation) = (3759.4668, 906.75) ft
PVT (distance, elevation) = (4039.4668, 898.5401) ft
Max. elevation(distance, elevation) = (3479.4668, 909.12415) ft

Curve(3) Length = 679.60596 ft
PVC (distance, elevation) = (4669.394, 878.5568) ft
PVI (dist_prj, elevation) = (5035.0, 869.35) ft
PVT (distance, elevation) = (5349.0, 876.9556) ft
Min. elevation(distance, elevation) = (5064.905, 873.51495) ft

Curve(4) Length = 621.44775 ft

Figure 7. Report of roadway geometry design

Figure 8. Drive through animation

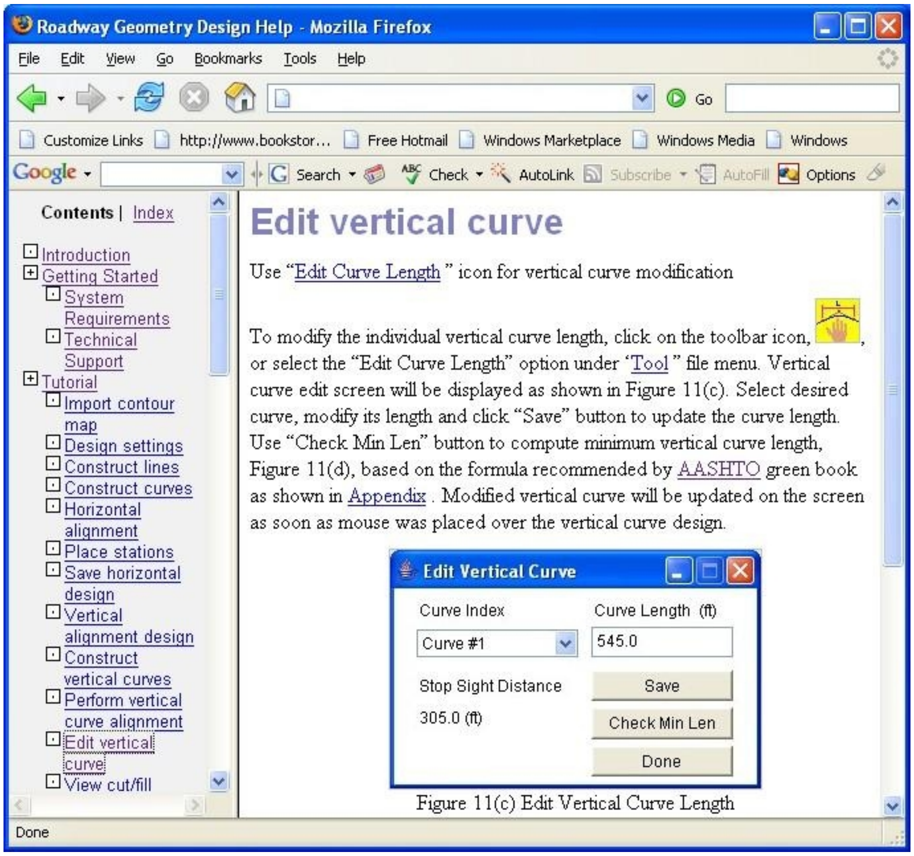


Figure 9. Online user's guide

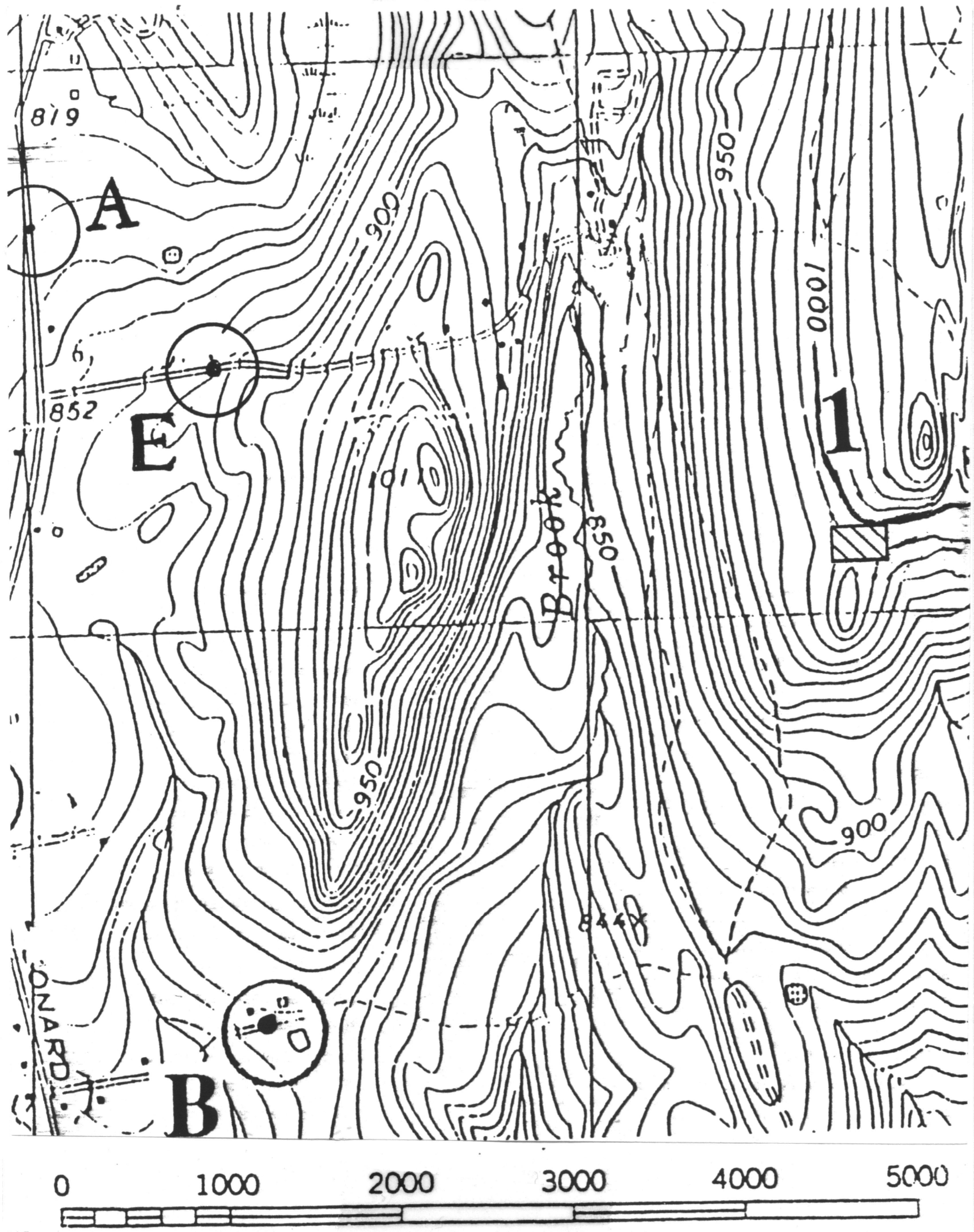


Figure 10 Topographic map for students project

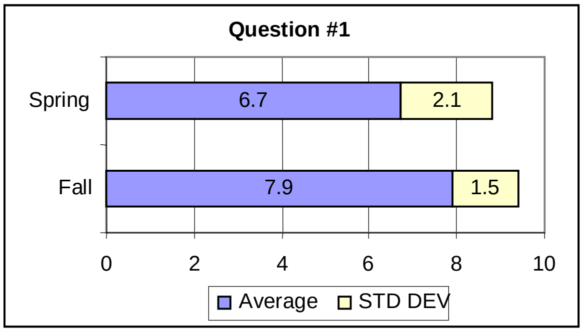


Figure 11(a) Question #1: Overall, the use of computer-aided tool makes me more enthusiastic about attending lab and/or working on project. (0: strongly disagree, 9: strongly agree)

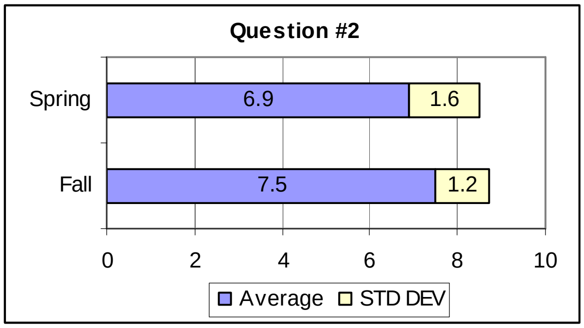


Figure 11(b) Question #2: This computer-aided design (CAD) approach enhances my learning. (0: strongly disagree, 9: strongly agree)

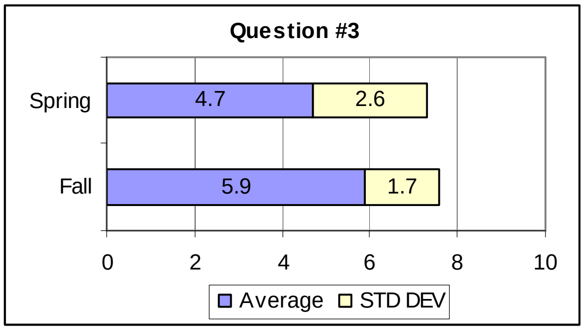


Figure 11(c) Question #3: Overall reaction to the roadway geometry design software. (0: frustrating, 9: satisfying)

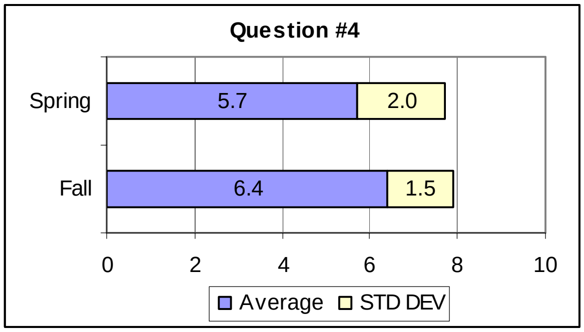


Figure 11(d) Question #4: Construct roadway geometry on PC screen is straightforward. (0: never, 9: always)

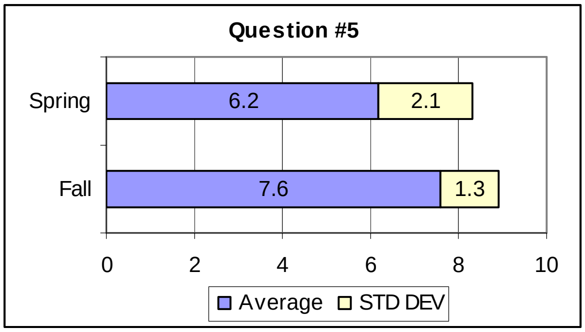


Figure 11(e) Question #5: The lab instruction helps me complete the lab assignment.
(0: strongly disagree, 9: strongly agree)

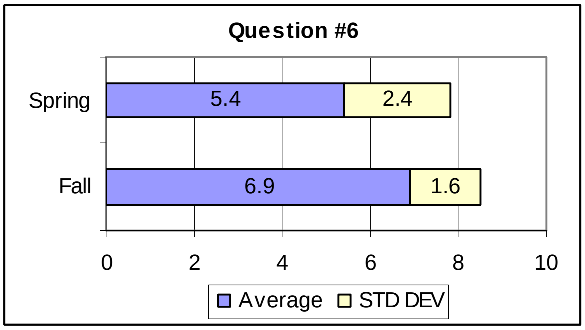


Figure 11(f) Question #6: User's manual or help document is, (0: confusing, 9: clear)

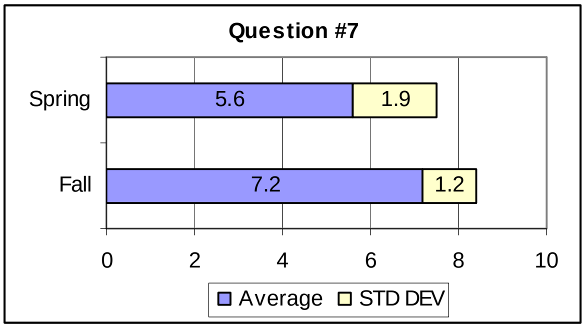


Figure 11(g) Question #7: The information (from screen or manual) is effective in helping me complete the project.
(0: strongly disagree, 9: strongly agree)

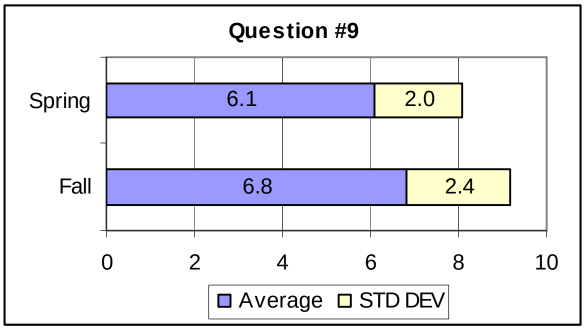


Figure 11(h) Question #9: The 3D animation helps me visualize my horizontal and vertical curve design and stopping. (0: strongly disagree, 9: strongly agree)

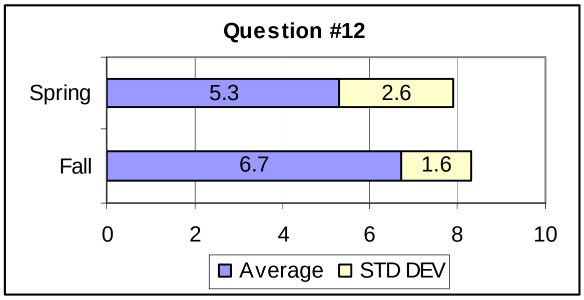


Figure 11(i) Question #12: Overall, I am satisfied with the amount of time it took to complete the lab assignment.
(0: strongly disagree, 9: strongly agree)